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Demonstration of enhanced radiation drive in hohlraums made with high-Z mixture "cocktail" wall materials

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Abstract: We present results from experiments, numerical simulations and analytic modeling, demonstrating enhanced hohlraum performance. Care in the fabrication and handling of hohlraums with walls consisting of high-Z mixtures (cocktails) has led to our demonstration, for the first time, of a significant increase in radiation temperature compared to a pure Au hohlraum that is in agreement with predictions and is ascribable to reduced wall losses. This data suggests that a NIF ignition hohlraum made of a U:Au:Dy cocktail should have ~17% reduction in wall losses compared to a similar gold hohlraum.

Maximizing the hohlraum coupling efficiency (ratio of capsule absorbed energy to laser energy) for indirectly-driven inertial confinement fusion experiments at the National Ignition Facility (NIF) is desired because it would allow one to drive an ignition capsule with the minimum laser energy. Hohlraum radiation energy balance is described by the following equation [1].

$$E_C = (E_{laser} - E_{Scatter})\eta_{CE} - E_{wall} - E_{LEH} \qquad (1)$$

Here, E_C is the x-ray energy absorbed by the fusion capsule in the center of the hohlraum, (E_{Laser} - $E_{Scatter}$) is the laser energy delivered inside the hohlraum with backscatter losses accounted for, η_{CE} is the fraction of that energy that is converted to x-rays, E_{wall} is the x-ray energy lost into the hohlraum wall, and E_{LEH} is the x-ray energy that escapes out the laser entrance holes (LEHs). For a fixed E_C, which is set by the ignition capsule design, minimizing the wall losses helps one to minimize the amount of laser energy required for ignition, which has benefits for NIF laser optics lifetimes and facility operating costs. For this reason currently proposed NIF ignition hohlraums are to be made of uranium-based cocktails that are predicted to have very low wall losses [2,3]. In this work, we show that a hohlraum made from a combination of U, Au, and Dy does indeed have E_{wall} that is lower than a gold hohlraum of the same size by the theoretically predicted amount. This experimental validation increases confidence in the physics basis of these NIF ignition hohlraums.

The x-ray losses into the hohlraum wall are well modeled as a radiation ablation front diffusing into a cold wall, the so-called Marshak wave [4]. Using Hammer and Rosen's similarity solutions for a subsonic heat front (with their power law fits in temperature, T, and density, ρ, to specific heat, ε, and opacity, κ) [5,6], we can show that the wall loss per area for a gold wall exposed to a temperature radiation source for a time t is given by

$$E_{wall}/A_{wall} \sim ({\varepsilon_0}^{0.7}/{\kappa_0}^{0.4})T^{3.3}(t)\cdot t^{0.6} \qquad (2)$$

This shows that in order to reduce the wall loss, we need a wall material that has both low specific heat (ε) and high opacity (κ) [6,7]. The emphasis on specific heat is of particular importance in this work. To date the predominant focus of the field has been on opacity. It has long been known that suitably chosen mixtures of materials ("cocktails") having overlapping energy bands should have a higher opacity than any single material because the low opacity of one material in one spectral range is compensated for with another material's high opacity in the same spectral range. This strategy was suggested for use in enhancing x-ray conversion efficiency [8], and, most relevant to this work, in reducing wall loss [9]. Colombant, et al. [10] performed a numerical study using the STA opacity model [11] in which they found various combinations of materials having higher Rosseland mean opacities than gold at 250 eV and 1 g/cc. Orzechowski, et al. [9] showed using side-by-side burn-through measurements that a gold/gadolinium cocktail foil burned through later than a gold foil of the same areal density, and thus inferred that the cocktail had a higher opacity than pure gold, in agreement with their estimates based on the XSN average atom model [12]. Olson, et al. [13] simultaneously measured the burn-through and re-emission of side-by-side Au and Au:Dy:Nd foils and found that although the burn-through data could be consistent with higher cocktail opacity, there was no evidence of higher cocktail re-emission, implying no reduction in wall loss.

These foil sample experiments seemed to show promise for cocktails, but because of the re-emission results, they were ultimately inconclusive. To further clarify the situation, we undertook to test the relative performance of cocktails versus gold in the most direct way, via integrated hohlraum experiments. The point of departure for this work was the numerical study by Suter [3] in which he analyzed many combinations of materials in order to find ones that minimized wall losses for an ignition design having a 250 eV peak drive temperature. These were Lasnex calculations [14] in which a Planckian radiation source was applied at the boundary of a one-dimensional slab of material. He found that the mixtures with the lowest wall losses invariably included uranium. In retrospect, this is because specific heat scales as $(Z_B+1)/A$, where Z_B is the ionization state, and A is the atomic number. At a given T, the higher the A, the lower the specific heat. We redid this analysis for a NIF ignition drive having a 300 eV peak drive temperature [2] and found that a combination of 60% U, 20% Dy, and 20% Au (atom %) minimized the wall losses. Fig. 1 shows the Lasnex (using STA) prediction that for this drive the U:Au:Dy cocktail has 17.5% less radiation wall loss than gold. When the LEH loss and capsule absorbed energy are included in our accounting, this means that the same capsule can be driven with 10% less laser energy if a gold hohlraum is replaced with the cocktail, which moves the laser further from its damage threshold.

The integrated hohlraum experiments reported here were performed at the Omega Laser Facility [15]. In these experiments we compared the radiation temperature (T) of Au and cocktail hohlraums that were heated with the same laser energy. We can equate a given measured increase in T to an equivalent reduction in wall loss via modeling. The experiment setup is shown in Fig. 2a. The hohlraums were heated by 40 beams using a 1 ns flat-top laser pulse with a total energy of up to 19.5 kJ. The radiation temperature was inferred from a time-resolved measurement of the spectrally-integrated radiation flux out of the LEH using a broadband 10 channel soft x-ray spectrometer ("Dante") [16] over an energy range from 0-5 keV. The radiation temperature (T) is defined as the spectrally integrated flux divided by the effective x-ray source size given by the LEH area as viewed from the Dante line of sight. The source size was measured with a filtered soft x-ray framing camera. The backscattered laser energy due to Brillouin (SBS) and Raman (SRS) Scattering was measured on two beams using the full aperture backscatter station (FABS).

Two different size hohlraums were utilized to span the radiation temperature range of interest. The large hohlraums were 1.2 mm in diameter, 2.06 mm long, and had LEH diameters of 0.8 mm. When heated by 5 kJ of energy, these were expected to reach a peak T (for gold hohlraum) of 185 eV. When heated by 19 kJ, the expected peak rises to 275 eV. The smaller hohlraums were 1.0 mm diameter, 1.6 mm long, had 0.67 mm diameter LEHs, and reached a peak T of 305 eV when heated by 19 kJ.

Our first attempts at demonstrating an increase in T [17] resulted in a surprisingly small increase. We hypothesize that those results and the surprising results from the Olson foil re-emission experiments might both be explained by oxygen contamination, which would significantly raise the heat capacity of the cocktails by increasing the average $(Z_B+1)/A$ of the mixture, and thus increase the wall loss. Indeed the measured 40% oxygen contamination of the Olson foils [18] would raise ε sufficiently to explain the Olson re-emission results. So, for the experiments reported here, the amount of oxygen in the cocktail coating material was carefully controlled using a new hohlraum manufacturing process. The new process employs a gold substrate hohlraum split in two along the hohlraum axis producing two shaped halves (see Fig. 2b). A total of 5μm of cocktail material is co-sputtered onto the inside surface of the halves. Note that instead of pure U, we used U alloyed with Nb, since this was readily available. Thus the actual cocktail mixture we tested was $U_{.52}Nb_{.08}Au_{.2}Dy_{.2}$. The inclusion of this amount of Nb results in a slight degradation of the cocktail performance, which was accounted for in our modeling. The cocktail is then over-coated with 0.2 μm Au liner. This thin Au liner serves to prevent oxygen from getting to the cocktail material. The two halves are then joined to form the hohlraum (the gold hohlraums were also constructed this way). All hohlraums had a wall thickness of 100 μm. The finished hohlraums were stored in nitrogen filled containers until one hour before each experiment. Calibrated flat witness plates were coated at the same time as the hohlraum halves. The material compositions of the witness plates were analyzed using Auger spectroscopy. We found that there was only a thin (0.1 micron) layer directly underneath the 0.2 μm protective Au layer that contained only 5-10% oxygen, and that deeper into the cocktail there was no detectable oxygen. This amount of oxygen remained stable for weeks in a controlled nitrogen atmosphere, and is predicted to have a negligible influence on the wall loss.

In this work, the key measurement is the difference in flux between the cocktail and gold hohlraums, so it is the relative error in the measurement that is important. Since the fluxes we are measuring are close to each other in absolute magnitude, the systematic errors in the Dante diode calibrations largely cancel out, although some random diode error remains. Additional sources of error in this measurement are due to uncertainties in the source size, the hohlraum size, the total laser power and energy, the laser power and energy of the beams directly viewed by Dante, the backscattered energy, and random errors in the Dante diode and unfold.

To estimate these errors, we introduce a simple energy balance model for a gold hohlraum. We start by modifying Eq. (1) to account for the fact that these hohlraums did not contain a capsule.

$$(E_{laser} - E_{Scatter})\eta_{CE} = E_{wall} + E_{LEH} \qquad (3)$$

Assuming that the radiation temperature for the 1 ns Omega experiments rises with T $\sim t^{0.18}$, which is consistent with our measurements, the wall loss (in MJ) for a gold hohlraum is [6]

$$E_{wall\_Au} = A_{wall} \cdot 0.39 \cdot T_0^{3.3} \cdot t^{1.18} \qquad (4)$$

where T_o is the peak radiation temperature (in heV) at 1 ns, A_{wall} is the hohlraum wall area is in mm^2, and t is time in ns. The losses out the LEH are [6]

$$E_{LEH} = A_{LEH} \cdot 0.58 \cdot T_0^{4} \cdot t^{1.72} \qquad (5)$$

The conversion efficiency in this model is

$$\eta = 0.85\, t^{0.2} \qquad (6)$$

Solving equations (3)-(6) yields a T(t) that agrees reasonably well with our gold hohlraum data. With this model, we find that the estimated uncertainties in wall area (2%), LEH area (2%), and absorbed (backscatter subtracted) laser energy (2%) yield an estimated error in the relative flux measurement of 3.2%. The additional uncertainty due to a 3% shot-to-shot variation in the total brightness of the laser spots visible in the Dante field of view is estimated to be an additional 1%. Adding in an estimated 4% random error from the Dante instrument [16], the total expected error in the relative flux measurement is 5.2% (1.3% in T).

Fig. 3 shows the measured time history of the radiation flux for two consecutive experiments (one cocktail, one gold) having a nominal peak T of 275 eV. Also shown on the same plot are the laser power histories. The total laser energy for these shots was 19.18 kJ (cocktail) and 19.29 kJ (gold), the total energy for the beams viewed by Dante differed by ~2%, and the backscatter was ~4%. After initially applying the laser pulse, the inferred radiation temperature increases in ~300ps to a value of 230eV. Afterwards it continues to increase more slowly with time ($\sim t^{0.18}$) as assumed in the analytic estimates. The cocktail flux begins to rise above the gold flux at about 0.4 ns. By the peak of the pulse, the inferred cocktail temperature is ~6 eV above the gold, which is greater than the relative error of these measurements. The Dante spectrum at the peak of the drive (Fig 3 insert) indicates that the cocktail is more advantageous below 2 keV, where most of the energy of the drive spectrum resides. The source size was monitored using the soft x-ray imager with 50 ps temporal resolution and we saw no appreciable LEH closure.

We used a simple energy balance semi-analytical model and more detailed integrated Lasnex simulations of the experiment to compare against the measurements. For the simple model we use Eqs (3)-(6) to get T(t) for the gold and then use that as a source for high resolution one-dimensional Lasnex calculations of cocktail and gold slabs to find the wall loss for each material. We then take the time-dependent ratio of the cocktail wall loss to the gold wall loss, multiply Eq (4) by that factor, and then solve for the cocktail T(t). Note that the implicit assumption that the x-ray conversion efficiency is unchanged in these experiments is based on fact that the laser does not ablate deeper than the 0.2 micron gold protective layer. For the full 2-D Lasnex calculations we model the entire problem in an axially symmetric computational grid, including the laser deposition, conversion to x-rays, and x-ray losses. This allows us to use the measured laser power and source size for each simulation. The temperature is obtained from the LEH flux (as in the experiment) by post-processing the simulation results from the Dante view angle.

The results of both models and the data from Fig. 3 are plotted on Fig. 4 in terms of $\Delta T = T_{cocktail} - T_{Au}$. The measured time-dependent increase in T agrees quite well with theory. The time-dependence is due to two factors. Until the Marshak wave has ablated past the 0.2 micron gold coating, we expect no difference. Also, from analytical scaling laws [6], we expect the cocktail wall loss to gold wall loss to scale as $T^{-0.2}$, so as the temperature rises during the experiment, the relative advantage of the cocktail keeps increasing.

We analyzed the 185 eV and 305 eV (nominal peak gold T) hohlraums in the same way as the 275 eV hohlraums above. From Lasnex the calculated cocktail to gold wall loss ratio at 1 ns is 97.6% for 185 eV, 90.8% for 275 eV, and 88.6% for 305 eV (confirming the analytically predicted $T^{-0.2}$ scaling). Even at the highest temperature the reduction in wall loss energy is lower than for NIF because of the relatively larger importance of rise time and gold layer overcoat thickness in the shorter duration Omega experiments. Fig. 5 shows the difference in T at the peak of the drive (relative to the average gold peak T) for all the experiments as a function of the nominal peak gold radiation temperature. The data (gold=circles, cocktail=squares) were normalized to the same absorbed laser energy using Eqs. 3-6. There is some scatter in the data, but for 275eV and above, all of the cocktail points lie above all of the gold points, and the increase in ΔT with T agrees with semi-analytical (solid line) and Lasnex 2D (blue circles) predictions. There is one low data point at 305 eV (from a different day than the other 305 eV cocktail points) for which the coating depth was not verified, so an insufficient cocktail layer depth could possibly explain the discrepancy.

In summary we presented experiments demonstrating an increase in radiation temperature for U:Au:Dy cocktail hohlraums compared to similarly constructed gold hohlraums. This increase and its scaling with peak temperature agree very well with a semi-analytic model and integrated Lasnex calculations, showing that the increase is attributable to a reduction in the x-ray wall losses. This proof of principle experiment gives us confidence in ignition target design calculations that predict the U:Au:Dy cocktail will reduce wall losses compare to gold by ~17%, saving 10% in laser energy.

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Figure Captions:

Figure 1: Time-dependent radiation drive (left axis) for a 300 eV Cu-doped Be NIF ignition capsule design. The right axis shows the ratio of the radiation energy wall loss for a U:Au:Dy cocktail hohlraum to that of gold for this radiation drive.

Figure 2: (a) Experimental setup showing line of sight of x-ray spectrometer (Dante) and soft x-ray framing camera (XFRC), (b) drawing of cocktail hohlraum halves before assembly.

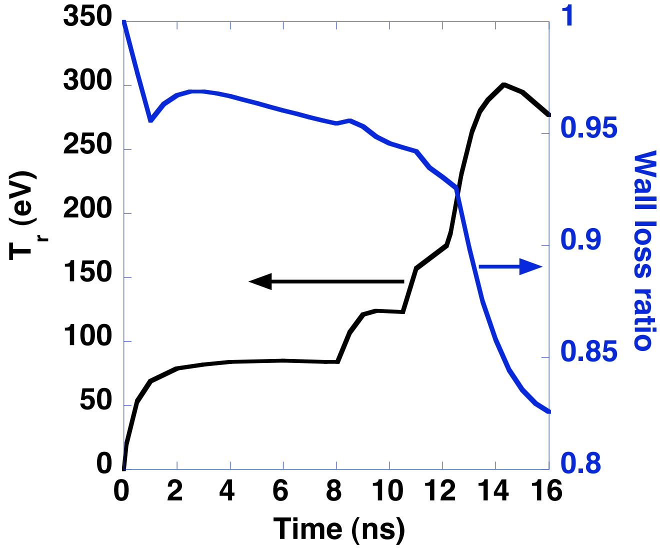
Figure 3: Laser power (left) and radiation flux (right) as function of time for two sequential “275 eV” experiments – gold (red circles, solid line) and cocktail (blue

squares, dashed line). Also shown (small insert) are the spectra at 1.1 ns as measured by Dante for Au (solid) and cocktail (dashed).

Figure 4: Increase in radiation temperature of cocktail relative to gold as a function of time for pair of sequential “275 eV” experiments. The data (squares) are compared to the simple semi-analytical model (red curve) and full 2-D Lasnex calculations (blue curve).

Figure 5: Increase in radiation temperature of cocktail relative to gold at time of peak drive as a function of expected peak gold hohlraum radiation temperature. Measurements for all experiments are shown with error bars and compared to semi-analytical model (solid line) and full 2-D Lasnex calculations (blue circles).

Figure 1 :



350
300
250
200
150
100
50
0
T
r
(eV)
1
0.95
0.9
0.85
0.8
Wall loss ratio
0
2
4
6
8
10
12
14
16
Time (ns)

Figure 2 :

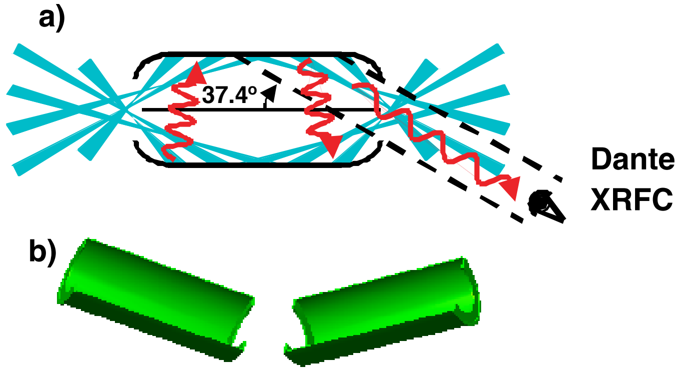
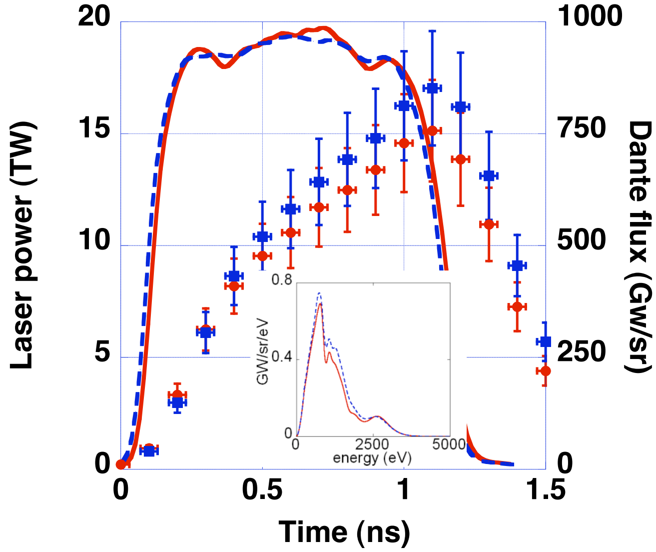


Figure 3 :



20
15
10
5
0
1000
750
500
250
0
Laser power (TW)
Dante flux (Gw/sr)
0
0.5
1
1.5
Time (ns)
0.8
0.4
0
GW/sr/eV
0
2500
5000
energy (eV)

Figure 4:

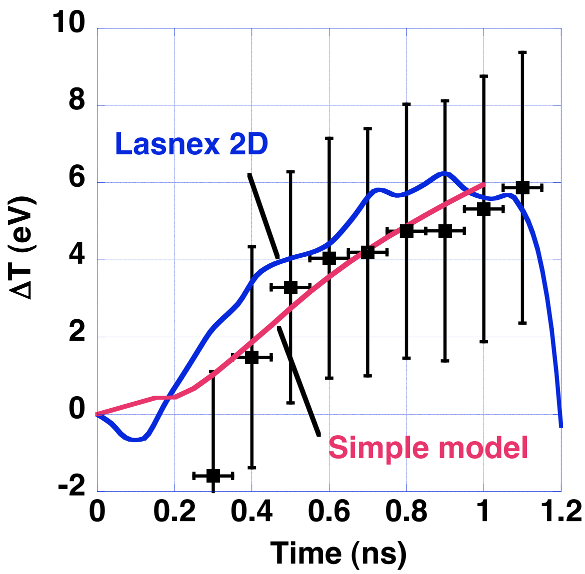
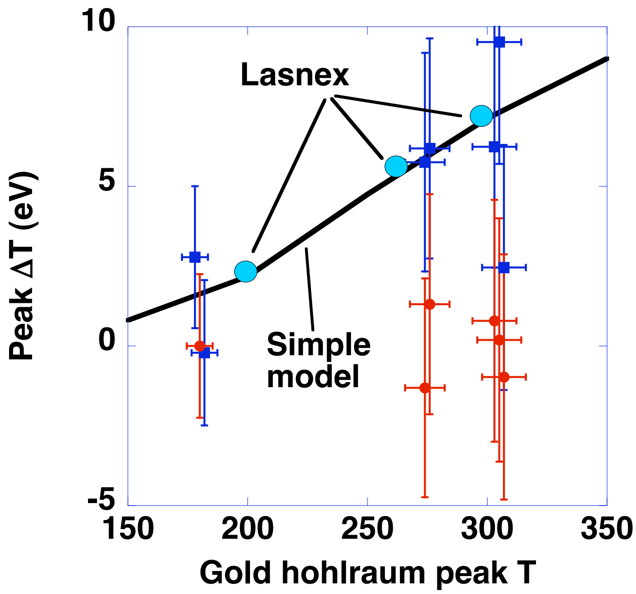


Figure 5:



Lasnex
Simple model
Peak ΔT (eV)
Gold hohlraum peak T
10
5
0
-5
150
200
250
300
350